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Terrestrial organic carbon storage in a British moorland

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Abstract

Accurate estimates for the size of terrestrial organic carbon (C) stores are needed to determine their importance in regulating atmospheric CO_2 concentrations. The C stored in vegetation and soil components of a British moorland was evaluated in order to: (i) investigate the importance of these ecosystems for C storage and (ii) test the accuracy of the United Kingdom's terrestrial C inventory. The area of vegetation and soil types was determined using existing digitized maps and a Geographical Information System (GIS). The importance of evaluating C storage using 2D area projections, as opposed to true surface areas, was investigated and found to be largely insignificant. Vegetation C storage was estimated from published results of productivity studies at the site supplemented by field sampling to evaluate soil C storage. Vegetation was found to be much less important for C storage than soil, with peat soils, particularly Blanket bog, containing the greatest amounts of C. Whilst the total amount of C in vegetation was similar to the UK national C inventory's estimate for the same area, the national inventory estimate for soil C was over three times higher than the value derived in the current study. Because the UK's C inventory can be considered relatively accurate compared to many others, the results imply that current estimates for soil C storage, at national and global scales, should be treated with caution.

Keywords: carbon storage, GIS, moorland, peat, soil, vegetation

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Introduction

Mean global air temperature is predicted to rise due to increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere (IPCC 1996). The response of terrestrial ecosystems to this anticipated climate change is uncertain, yet these ecosystems contain large amounts of organic carbon (C) and have the potential to influence future atmospheric CO_2 levels through changes in the balance between photosynthesis and respiration (Melillo *et al*. 1996) or through changes in land use (Schimel 1995). In particular, there is concern that higher decomposition rates following climate change may lead to a reduction in terrestrial C storage and create a positive feedback to global warming (Melillo *et al*. 1996) through increased transfer of C to the atmosphere.

Although models have been developed to predict the impact of future climate change on terrestrial C fluxes (e.g. Cao & Woodward 1998), accurate estimates for the size of present terrestrial C stores are needed to gauge the size of future C fluxes and provide a baseline against which to measure future change. Despite many estimates for global soil and vegetation C stores, a general lack of data and high inherent natural variability has meant that estimates for global C storage have ranged greatly with, for example, global soil organic C being estimated at 700×10^{12} kg and 2946×10^{12} kg (to 1 metre depth; Post *et al*. 1982).

The need for more accurate inventories of global soil and vegetation C was recognized at the 1992 Rio Earth Summit when signatories to the Climate Change Convention committed nations to evaluating national terrestrial C stores (United Nations 1993). Several of

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these national inventories have now been published (e.g. United Kingdom, Milne & Brown 1997; New Zealand, Tate *et al*. 1997), and their accuracy needs to be assessed.

Terrestrial C storage is usually quantified by multiplying the area of vegetation and soil type by the average C stored per unit area (C content) for each vegetation and soil. Uncertainty in the accuracy of these inventories arises as a consequence of: (i) problems in the classification of vegetation and soil; (ii) inaccurate area estimates; and (iii) unrepresentative values for C content of soil and vegetation types. Furthermore, most C inventories use area estimates derived from traditional 2D map projections which, unless the subject area is perfectly flat, will be an underestimate of the true surface area.

We quantified terrestrial C storage within a British moorland in order to: (i) determine the importance of these ecosystems for C storage, and (ii) compare the data with those published within the UK's national C inventory. We have also investigated the importance of using true surface areas, as opposed to 2D areas, for estimating C storage.

Materials and methods

Description of the study site

The Moor House National Nature Reserve (Fig. 1) in the northern Pennines of England was chosen for the study site. The Reserve can be considered typical of British moorland (Heal *et al*. 1975). It has a strong history of ecological research, being a major site in the International Biological Programme (Heal & Perkins 1978) and more recently in NERC's Terrestrial Initiative in Global Environmental Research (TIGER) programme (e.g. Ineson *et al*. 1998). As a result, Moor House provides a unique opportunity to quantify terrestrial C storage accurately because a large resource of detailed information, necessary for evaluating C stores, is already available.

Within Moor House, we defined a study area based on the 22 1-km^2 National Grid squares of the Ordnance Survey which fit entirely within the Reserve boundary (Fig. 2). This enabled our results to be compared directly with the UK national C inventory (Milne & Brown 1997) which contains a C-value for each square in the same 1-km grid system.

The vegetation of Moor House has been described and classified by Eddy *et al*. (1969) and a digitized version of their map has been used to illustrate the distribution of vegetation classes at the study site (Fig. 3). The dominant vegetation on the eastern side of the Reserve is typical for blanket mire (e.g. Calluneto-Eriophoretum) while extensive areas of upland grassland occur on the western side where slopes are steeper (Fig. 2).

The soils at Moor House have been mapped by Johnson & Dunham (1963; Fig. 4). The dominant soil type is Blanket bog although mineral soils are also represented. In areas where two or more soil types were repeatedly present, but changed from one to the other over short distances, the soils were mapped as complexes (Johnson & Dunham 1963). Hornung (1968) and Johnson & Dunham (1963) provide detailed descriptions of the soils at Moor House.

Area of vegetation and soil types

We quantified C storage in each vegetation and soil type by multiplying their area within the study site by estimates for their C content. To make a comparison with the UK's national inventory we also calculated C storage for each square kilometre of the study site by determining the area of different vegetation and soil types in each 1-km^2 square. Digitized versions of the vegetation map of Eddy *et al*. (1969) and soils map of Johnson & Dunham (1963) were analysed using a geographical information system (GIS; Arc/Info©, ESRI Ltd) to determine the area of vegetation and soil types.

Inventories of terrestrial C are usually derived using 2D and not true surface areas, yet the area estimate which should be used for quantifying C stores depends on how the C content values are derived. For vegetation, C content is derived from measurements of aboveground biomass which are usually determined by clipping representative plots (typically 0.5 m^2) and measuring the dry weight of vegetation removed (e.g. Forrest & Smith 1975). Because the area of these plots is measured along the surface of the ground, sloping plots with a true surface area of 0.5 m^2 will have a smaller 2D area, depending on the severity of the slope. Consequently, vegetation C storage will be underestimated if these C content values are extrapolated using 2D areas. Therefore, vegetation C stores should be calculated by multiplying C content by the true surface area.

We investigated the impact of quantifying vegetation C storage at Moor House using true surface and 2D areas. 2D areas were determined directly from the digitized vegetation map while true surface areas were calculated using a digital elevation model (DEM). The DEM was constructed from a 10-m contour coverage of the study site using Arc/Info©. This involved creating a triangular irregular network (TIN) where the surface of the study site was represented by sloping triangles (Peuker *et al*. 1978). True surface areas (and mean slopes) of the vegetation classes were calculated by combining the TIN with the digitized vegetation map of Moor House.

Unlike vegetation C stores, 2D areas should be used to evaluate soil C stores because the sampling methods for

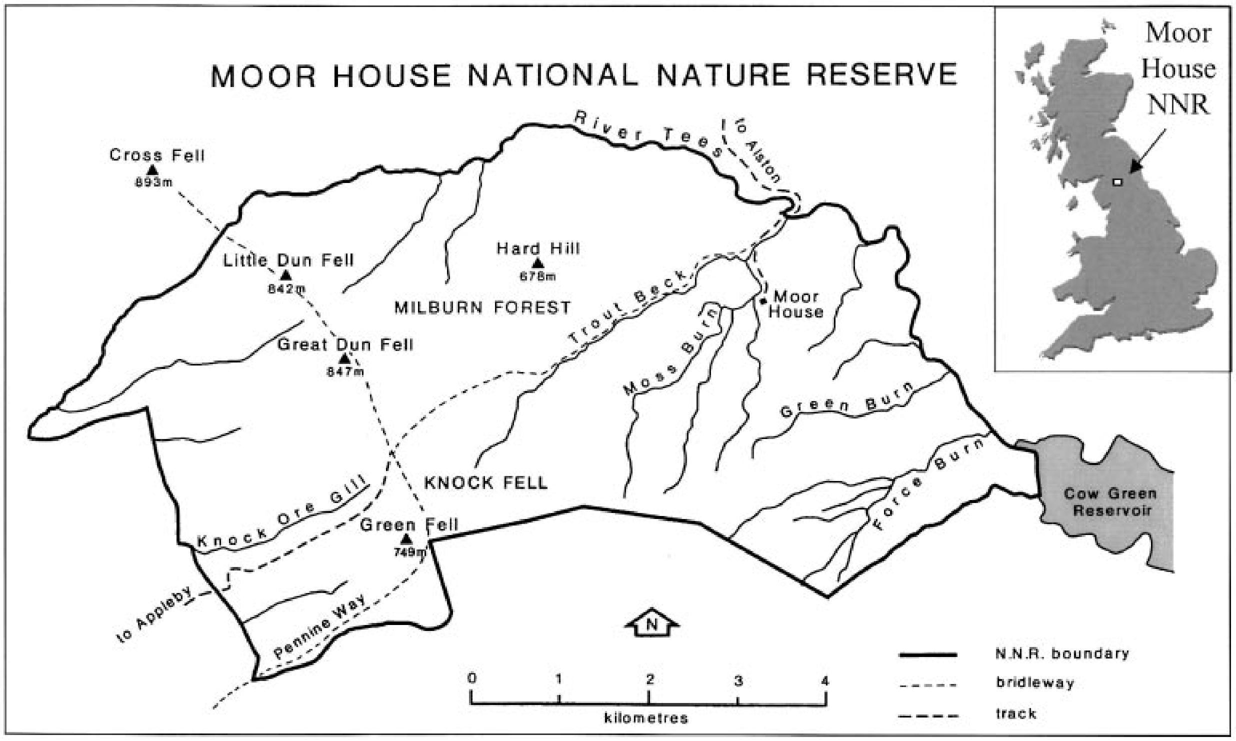

Fig. 1 Location of Moor House National Nature Reserve (NNR) within Great Britain.

soil C content account for variations in topography. Because soil profiles are traditionally sampled vertically, on sloping ground the depth sampled will be greater than the depth perpendicular to the slope. The increase in C storage per square metre resulting from this vertical sampling soil is directly proportional to the slope and therefore accounts for variations in topography.

Quantification of C content

Because many detailed productivity studies had already been published for Moor House, the results of these studies were used to derive estimates of C content for vegetation classes. However, aboveground biomass values were not available for several of the minor vegetation classes and C storage estimates were based on results from other locations in the UK, or used values derived for similar classes measured at Moor House. Vegetation biomass was assumed to have a C concentration of 47% (Allen 1989).

Suitable records for estimating soil C storage for the site were lacking and therefore a programme of field sampling was undertaken. A total of 166 locations were investigated between October 1995 and September 1997, covering all soil types except the Valley bog and 'soil complexes'; records were already available for the Valley bog while the C storage of 'soil complexes' was derived assuming equal proportions of component soils. Sampling points were located randomly within a soil type and were distributed across the study site. However, the Red-brown limestone and Solifluxion creep soils were investigated as part of a separate study (Garnett 1998) and, although not truly randomly sampled, were from representative areas.

It was apparent from an early stage that the Blanket bog was likely to be of particular importance for C storage based on area, and therefore, this soil type was stratified according to vegetation class in an attempt to further improve the C storage estimate. It was expected that stratification by vegetation would lead to an improved estimate of C storage, as other studies have shown mire vegetation to be controlled strongly by hydrology (e.g. Bubier 1995), which is itself extremely important for peat accumulation (Clymo 1984). Fifty Blanket bog sampling points were investigated, the number in each strata being weighted according to the proportion of the total area of Blanket bog the strata occupied.

Because of the very different nature of the soils at Moor House it was necessary to use several alternative methods to collect soil samples. Organic soils were sampled using a stainless steel corer ($5 \times 5 \times 100$ cm; Cuttle & Malcolm 1979) and in most cases a complete vertical profile was collected. The profile was sectioned at depth intervals of 30, 50 and 100 cm and the complete samples retained and used to determine bulk density and

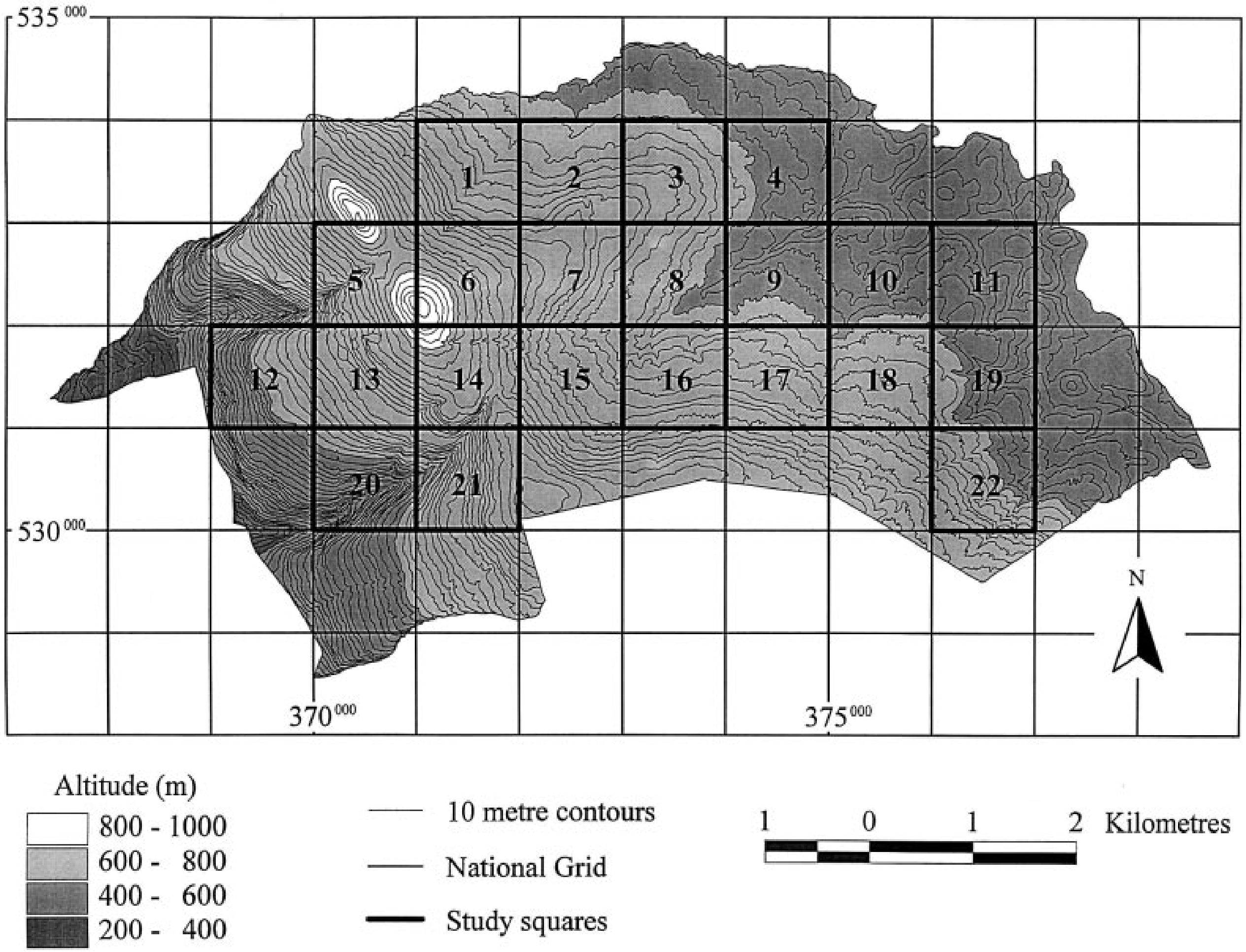

Fig. 2 Topography of Moor House NNR and location of the 22 1-km^2 squares of the study area. Reference numbers for each square are shown.

%C content. All other soils were sampled using a small cylindrical soil corer (diameter 3.6 cm and length 26 cm) or by digging pits and collecting representative samples from the profile in aluminium containers of known volume (bulk density tins).

All soil samples were oven dried (105 °C) to constant weight, sieved (2 mm mesh) and weighed to determine bulk density (dry mass divided by fresh volume). Loss on ignition (%LOI) was determined for each sample following the method of Allen (1989) and used to estimate the %C of the soil by applying a regression previously derived for Moor House soils (Bol *et al*. 1999). The C content (kg m^{-2}) of individual soil types was calculated from the %C, depth and bulk density values.

Results

Vegetation C stores

Table 1 provides the 2D and true surface areas of vegetation classes within the study site. The Calluneto-Eriophoretum class was dominant, covering about one third of the site. The true surface area of the entire site was only 1.2% greater than the 2D area, despite the varied topography (Fig. 2). As expected, the proportional increase in area was related directly to the severity of slopes with, for example, vegetation classes on the gently sloping blanket peat having a true surface area only slightly greater than the 2D.

Table 1 also presents values of aboveground biomass and C content for each vegetation class represented in the study area, together with the published sources of these data. The vegetation class with the highest C content was Pteridietum with mean aboveground biomass of 1010 g m^{-2}. Grasses mainly dominated the vegetation classes with the lowest C contents (e.g. Agrosto-Festucetum).

The total C stored in vegetation classes at Moor House is given in Table 1 and its spatial distribution presented in Fig. 5. Almost half of all vegetation C was in the Calluneto-Eriophoretum class with an estimated

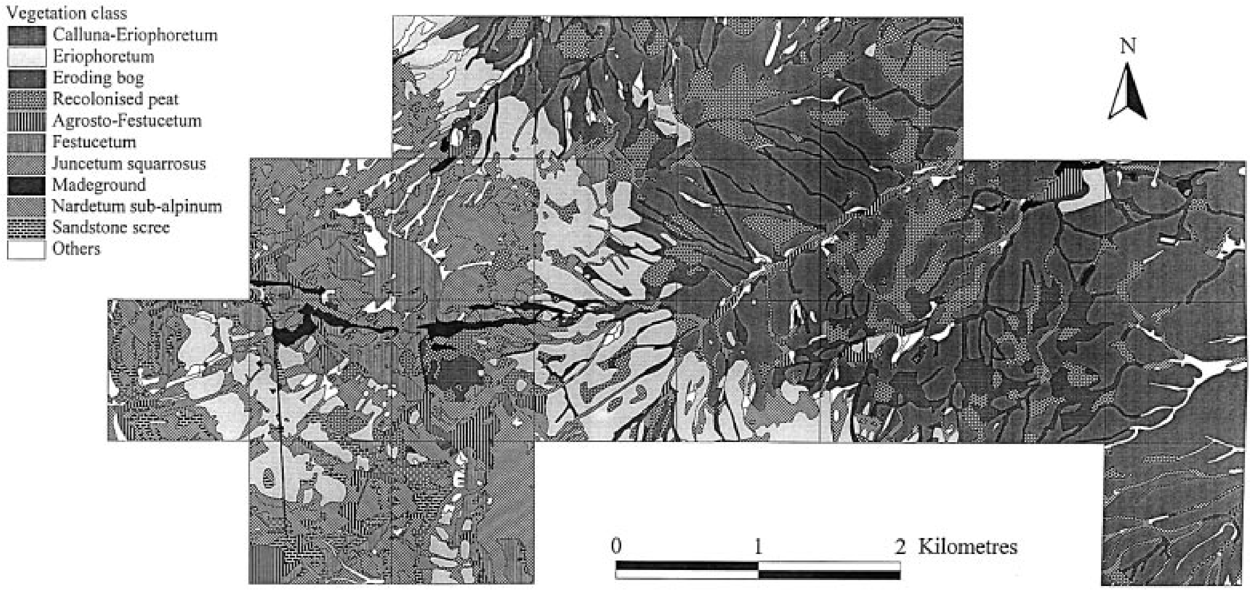

Fig. 3 Map of vegetation classes within the study area at Moor House NNR (derived from Eddy *et al*. 1969).

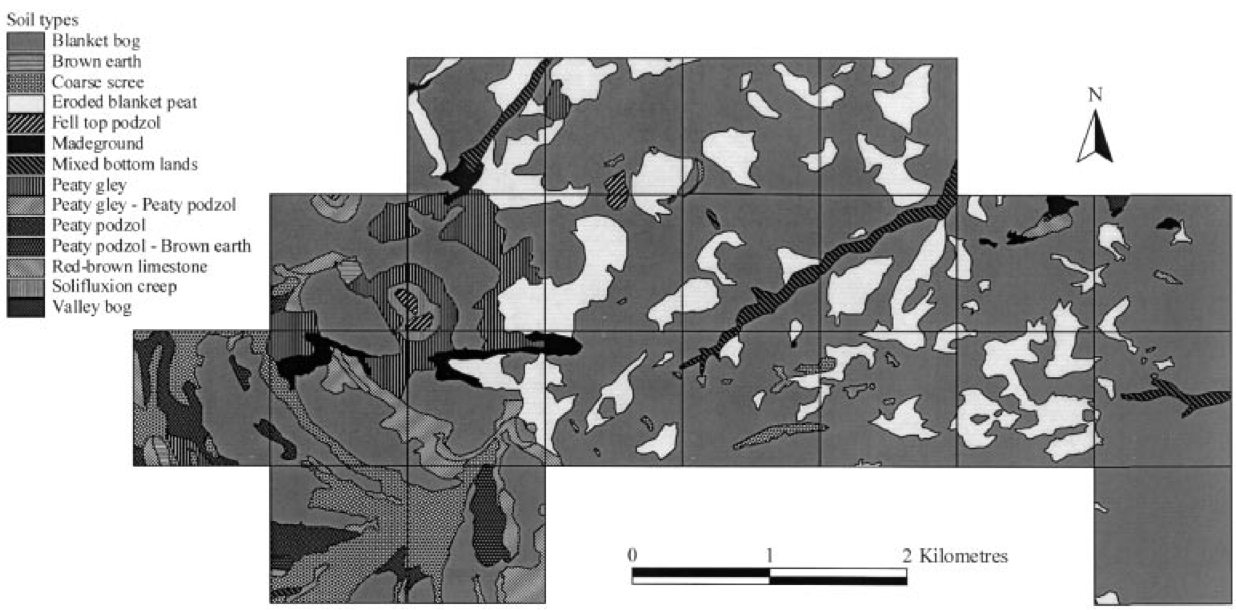

Fig. 4 Map of soil types within the study area at Moor House NNR (derived from Johnson & Dunham 1963). See Appendix for correlation between the Moor House soil types and FAO soil classes.

2.6×10^6 kgC, out of a total 5.4×10^6 kg for the entire study area.

Soil C stores

The 2D areas of soil types at Moor House are shown in Table 2. The dominance of Blanket bog within the study site is clear, with Calluneto-Eriophoretum bog occupying the greatest area.

It was noticed that a small amount of compaction occurred when coring the blanket bog and this was investigated to determine what effect it may have on the estimates of C storage. We determined from a range of sites that compression of between 1 and 7 cm (mean 3.9 ± 0.9 cm; SE) occurred during coring. By inserting the corer and excavating the surrounding peat we observed from the peat stratigraphy that all compaction occurred in the top 30 cm of the core. Where necessary, we have

Table 1 True surface and 2D area, mean slope, C per square metre and total C storage in vegetation classes at Moor House based on true surface and 2D areas. The classes have been ordered by area.

Vegetation class	True surface area ($m^2 \times 10^3$)	2D area ($m^2 \times 10^3$)	Mean slope (%)	Aboveground biomass ($g\ m^{-2}$)	C content ($g\ m^{-2}$)	Total C storage ($kgC \times 10^3$)	C storage using 2D area ($kgC \times 10^3$)
Calluneto-Eriophoretum	7415	7376	7	776 [3]	349	2589	2576
Eriophoretum	2919	2896	11	432 [4]	194	567	563
Nardetum subalpinum	2634	2571	22	250 [1]	113	296	289
Recolonized peat	2181	2172	8	776 [3]	349	762	758
Eroding bog	1834	1827	7	776 [3]	349	641	638
Juncetum squarrosus	1731	1708	16	275 [5]	124	214	211
Festucetum	1258	1224	26	71 [5]	32	40	39
Agrosto-Festucetum	634	602	34	46 [1]	21	13	12
Sandstone scree	455	431	33	71 [5]	32	15	14
Sphagneto-Juncetum	294	291	11	490 [2]	221	65	64
Madeground	282	278	16	46 [1]	21	6	6
Flushed gleys	252	248	16	490 [2]	221	56	55
Sphagneto-Caricetum	229	226	17	490 [2]	221	50	50
Calcareous springs	100	98	18	490 [2]	221	22	22
Pteridietum	53	52	24	1010 [2]	455	24	24
Trichophoro-Eriophoretum	2	2	7	188 [4]	85	0	0
Total	22,273	22,000				5360	5321

Sources of biomass values: [1]Smith & Forrest (1978), [2]Pearsall & Gorham (1956), [3]Forrest (1971) in Smith & Forrest (1978), [4]Forrest & Smith (1975), [5]Rawes & Welch (1969).

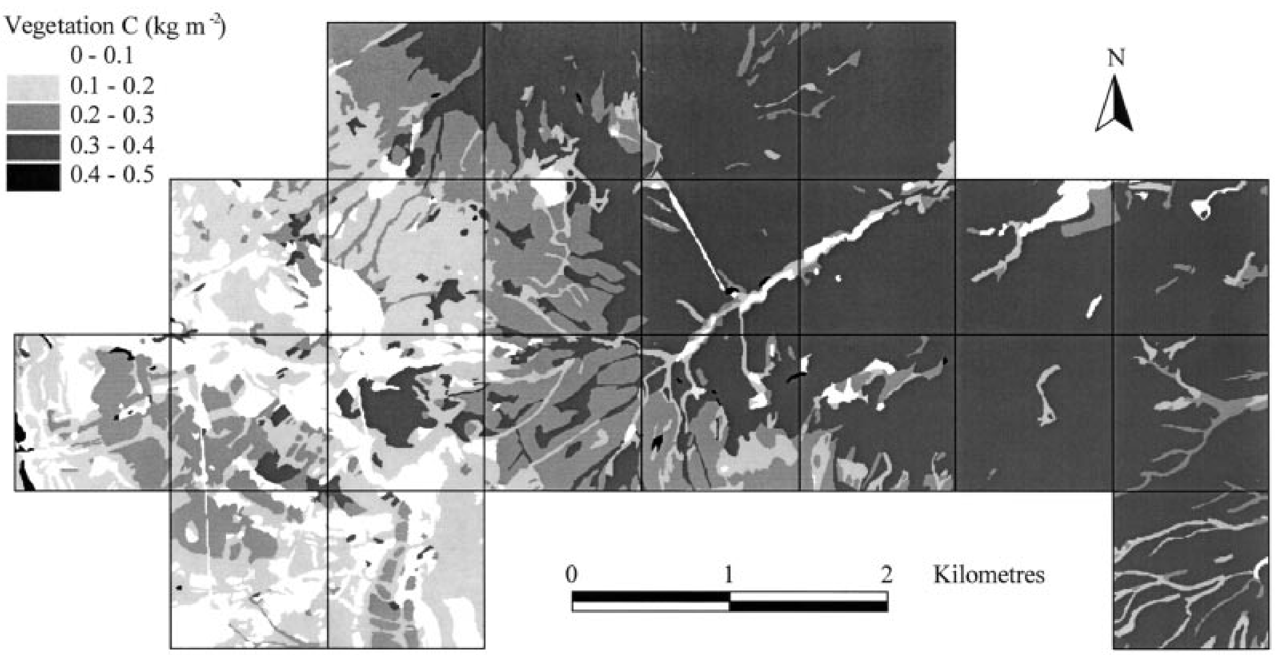

Fig. 5 Map of vegetation C storage at Moor House derived in the present study.

therefore compensated for the effect of compression during coring by assuming an average compaction of 3.9 cm in the top 30 cm of each profile. However, this had only a minor effect on the results and reduced the total C storage estimate by less than 1%.

The C contents of each soil to different depths are shown with standard errors, where obtained (Table 2). The range of C contents for soil increased when considering soil C to increased depth; for example, soil C to 30 cm for most soils was between 10 and 20 $kg\ m^{-2}$

Table 2 Area (2D) and C per square metre (with standard error where available) in top 30 cm, 50 cm, 100 cm and total depth of soil types at Moor House. Soil types have been ordered by area. NS = not sampled.

Soil type	2D area ($m^2 \times 10^3$)	Sampling points	C content ($kg\ m^{-2}$)			
			Top 30 cm	Top 50 cm	Top 100 cm	Total depth
Calluneto-Eriophoretum bog	7234	25	13.5 ± 0.4	23.0 ± 0.5	44.6 ± 1.5	85.4 ± 6.4
Eriophoretum bog	2696	8	17.6 ± 1.3	27.8 ± 2.3	35.6 ± 3.5	44.6 ± 7.1
Recolonized bog	2074	4	13.1 ± 2.0	21.0 ± 4.0	28.9 ± 9.0	45.2 ± 24.7
Eroding bog	1725	4	11.9 ± 3.8	19.8 ± 6.1	28.5 ± 9.4	50.7 ± 30.0
Nardetum bog	1423	5	14.5 ± 1.4	24.8 ± 3.9	37.1 ± 6.0	37.5 ± 6.1
Other blanket bog	1275	NS	14.1 ± 0.5	23.4 ± 0.9	38.8 ± 1.8	63.8 ± 5.4
Coarse scree[a]	1212	3				11.6 ± 2.0
Juncetum bog	1186	4	13.1 ± 3.2	21.2 ± 6.4	31.8 ± 11.2	31.8 ± 11.2
Peaty gley	900	34	12.1 ± 0.8	15.4 ± 1.2	16.3 ± 1.4	16.3 ± 1.4
Peaty gley-peaty podzol	496	NS	16.0	17.6	18.1	18.1
Peaty podzol[a]	377	5				19.8 ± 3.4
Mixed bottom lands	361	NS	8.0	12.4	19.7	32.2
Red-brown limestone[b]	352	16	9.8 ± 1.3			12.0 ± 1.7
Madeground[a]	290	3				4.3 ± 0.9
Peaty podzol-brown earth	179	NS	16.4	18.7	19.5	19.5
Solifluxion creep[a]	97	24				2.9 ± 0.2
Fell top podzol[a]	70	3				13.6 ± 4.6
Brown earth	42	28	13.0 ± 0.4	17.6 ± 0.5	19.2 ± 0.8	19.2 ± 0.8
Valley bog	13	NS	4.7	7.0	16.7	256.4
Total	22,000					

[a] Soils with total depth < 30 cm; [b] Soil with total depth < 50 cm

Table 3 Total C stored in different soil types in top 30 cm, 50 cm, 100 cm and total depth of soil at Moor House. Soil types have been ordered by C stored in total soil depth.

Soil type	Total C stored ($kg \times 10^6$)			
	Top 30 cm	Top 50 cm	Top 100 cm	Total soil depth
Calluneto-Eriophoretum bog	97.9	166.5	322.4	617.8
Eriophoretum bog	47.5	74.8	95.9	120.1
Recolonized bog	27.1	43.5	59.9	93.6
Eroding bog	20.6	34.1	49.1	87.4
Other blanket bog	18.0	29.8	49.5	81.4
Nardetum bog	20.7	35.2	52.8	53.4
Juncetum bog	15.5	25.1	37.7	37.7
Peaty gley	10.9	13.8	14.7	14.7
Coarse scree	14.1	14.1	14.1	14.1
Mixed bottom lands	2.9	4.5	7.1	11.6
Peaty gley-peaty podzol	7.9	8.7	9.0	9.0
Peaty podzol	7.5	7.5	7.5	7.5
Red-brown limestone	3.5	4.2	4.2	4.2
Peaty podzol-brown earth	2.9	3.3	3.5	3.5
Valley bog	0.1	0.1	0.2	3.4
Madeground	1.2	1.2	1.2	1.2
Fell top podzol	0.9	0.9	0.9	0.9
Brown earth	0.5	0.7	0.8	0.8
Solifluxion creep	0.3	0.3	0.3	0.3
Total	300.0	468.5	730.7	1162.6

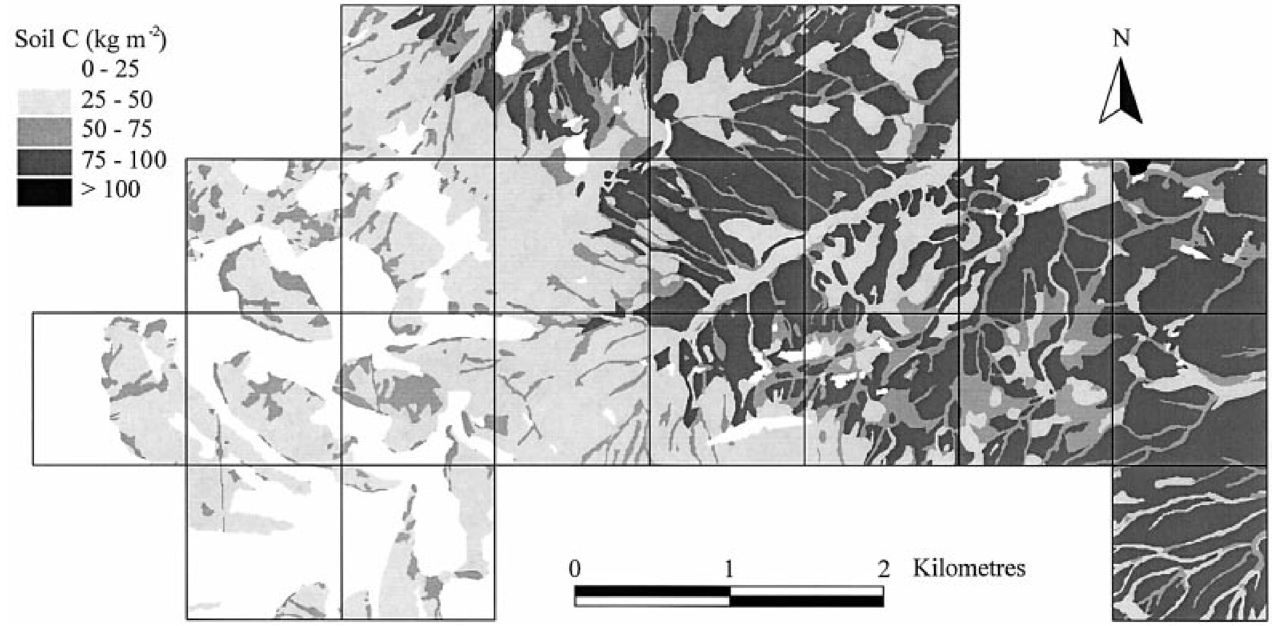

Fig. 6 Map of soil C storage at Moor House derived in the present study.

Table 4 Soil C in each 1-km^2 square at Moor House in top 30 cm, 50 cm, 100 cm and total soil depth derived in the current study. All units are kgC $\times 10^6$.

	Total C stored (kg $\times 10^6$)			
Kilometre square (see Fig. 2)	Top 30 cm	Top 50 cm	Top 100 cm	Total soil depth
1	14	23	34	47
2	14	22	36	62
3	13	22	39	71
4	13	22	38	70
5	13	19	27	32
6	13	19	26	29
7	16	25	35	49
8	13	22	39	71
9	13	21	36	65
10	13	22	38	68
11	13	22	41	79
12	15	19	23	27
13	14	19	25	30
14	13	18	25	32
15	15	24	33	44
16	14	23	36	56
17	14	22	37	64
18	13	21	36	65
19	13	22	41	77
20	14	17	20	22
21	14	19	23	26
22	14	23	42	75
Total	300	469	731	1163

and from below 10 kg m^{-2} to more than 100 kg m^{-2} for total soil depth. Peat soils had the highest soil C content when considering the total depth (e.g. Valley bog and Calluneto-Eriophoretum bog), whereas some of the shallow mineral soils had considerably lower *C*-values (e.g. Solifluxion creep).

Table 3 shows the estimated C stored within each soil type for the entire study area to different soil depths. For all depths the blanket bog soil types contained the most C (particularly Calluneto-Eriophoretum) and although the Valley bog soil had by far the greatest C content in its full depth (Table 2), the total amount of C it contained was small compared to other soil types because of its small areal extent within the study area. The spatial variation in soil C storage (Fig. 6) clearly shows the importance of the different strata of blanket bog.

Table 4 displays the soil C storage values to different depths for each 1-km^2 square within the study site. Clearly, C storage increased when greater soil depth was considered, however, the extent of the increase depended on the soil types present in each square. For example, squares dominated by shallow soils only had slightly more soil C in the top 100 cm than in the top 30 cm (e.g. square 20; difference = 6 $\times 10^6$ kgC), whereas squares containing blanket bog had much greater amounts of C storage when considering the same depths (e.g. square 22; difference = 28 $\times 10^6$ kgC).

Discussion

Reliable estimates of C storage are required to assess the importance of terrestrial ecosystems in the global C cycle, particularly with the current need to understand the influence of terrestrial ecosystems on atmospheric CO_2 concentrations. Although it is the terrestrial C fluxes and not the size of C stores which directly affect atmospheric CO_2 concentrations, inventories of present C stores are useful for providing baselines against which future change can be measured.

The usefulness of these C inventories depends on their accuracy and the detail of information available for quantifying C storage at Moor House provided a unique opportunity to test the accuracy of one such national C inventory. Although the UK has only a small proportion of the Earth's terrestrial C store, it contains about 13% of global blanket bogs (Lindsay *et al*. 1988) and the results from this verification exercise have implications for terrestrial C inventories elsewhere.

As with other terrestrial C inventories, uncertainty exists within (i) estimates of vegetation and soil area and (ii) the C contents assigned to vegetation and soil types (Batjes & Sombroek 1997).

Great care was taken in the present study to accurately determine the area of vegetation and soil types at the site. Areas were calculated using digitized versions of soil and vegetation maps of exceptional detail for an upland ecosystem. However, vegetation, and soils in particular, are very difficult to map and it is likely that some error was introduced during field surveying.

Uncertainty in the C content values for different vegetation classes can generally be considered low because the results of numerous productivity studies performed at the site were used, and the values were consistent between studies. However, there may be some inaccuracy in a few of the minor vegetation classes since no published values for these classes were available. The C contents assigned to these classes were based on values for similar vegetation classes although it is unlikely they significantly affect the overall C estimates since they represent a very small proportion of the study site (Table 1).

There is evidence to suggest that atmospheric N deposition may have increased at the site and therefore affected the vegetation C contents and distribution of vegetation classes since the original surveys (Gore 1968; Taylor *et al*. 1999). However, we have been unable to detect any consistent increases in C storage in our own recent measurements, and personal observation while undertaking field sampling at the site suggested that the distribution of vegetation classes had not significantly changed. Furthermore, the site has been managed as a Nature Reserve since 1952 and, therefore, there have been no recent changes in land-use (Heal & Smith 1978).

The main area of uncertainty in the estimates for soil C storage is believed to be the C content values assigned to soil types. Despite an extensive programme of field sampling, more representative estimates of C content could have been derived if the intensity of sampling had been higher. For example, the C content of several soils has been estimated from the mean of only three sampling points. Because time constraints limited the number of sampling locations investigated, the most intensive sampling was undertaken on soils which were expected to be most important for C storage; for example, a total of 50 Blanket bog sites were investigated, further sampling being largely hindered by the remoteness and inaccessibility of terrain. However, because sampling points were randomly located they can be considered representative and, although differences in the nature of soils meant several methods were used to obtain soil samples, comparison exercises between techniques suggested their accuracy for deriving C contents was consistent.

Compaction of peat samples while coring the blanket bog meant that a correction factor had to be used. Although alternative coring techniques which do not cause compaction could have been used (e.g. the freeze-corer of Harden *et al*. 1997) the effect of compaction on the final C storage estimate was small.

Initial attempts at determining soil C investigated the importance of slope, aspect and altitude by studying the variation in soil C content with each of these variables. These studies were conducted on a mineral (Brown earth) and peat soil (Peaty gley) because it was thought that if soil C content was strongly influenced by any of these variables, a more accurate estimate of soil C could be produced using the DEM of the site. However, none of the variables were significantly correlated with soil C content and further attempts to derive C storage estimates using this approach were considered unnecessary (see Garnett 1998).

Vegetation C storage

The true surface area of the study site was calculated to be only 1.2% greater than the 2D area although the increase differed between vegetation classes. However, the classes which increased most on correction tended to be ones with the lowest C contents and the increase in the estimate for vegetation C storage, after considering true surface area, was a lower percentage than the increase in area alone (C in vegetation based on true surface area was only 0.7% higher than the 2D estimate; Table 1). Although the application of true surface areas to quantify the Moor House vegetation C may have improved the overall C storage estimate, the increased accuracy was small compared to the errors associated with other aspects of evaluating vegetation C stores.

The vegetation class with the greatest C storage was Calluneto-Eriophoretum as it covered the greatest area and had a higher C content than many of the other vegetation classes. The other classes associated with the blanket peat also had high C storage due to their large area and high C contents. The greater C storage of the moorland vegetation classes when compared with the grasslands was probably at least partly a result of sheep grazing on the Reserve; the grasslands are more intensively grazed than the moorland vegetation classes and therefore appear not to accumulate large amounts of aboveground biomass.

Soil C stores

When considering only the top 30 cm, the Moor House soils generally had similar C contents. However, three soils had markedly lower values than the others, with Madeground and Solifluxion creep having low C contents due to the soils being less than 30 cm deep and having a low C concentration. The Valley bog soil type had a low C content in the top 30 cm because its bulk density was low near the surface (although its C concentration was high). When calculating C content to greater depths, the range in values increased because some soils were less than 30 cm deep and therefore their C content did not change, though other soils extended deeper (e.g. the Blanket bog soils) and their C contents increased. The nonblanket bog soil types, by definition, had a peaty layer of less than 30 cm (Johnson & Dunham 1963), and because nonpeaty layers had a lower C concentration, the nonBlanket bog soil types did not increase their C contents as much as the Blanket bog soils, when considering greater soil depths.

It was clear from the results that a high natural variability in C content occurs within soil types. The standard errors for the sampled soils reflect this (Table 2), but because only a few sampling locations were investigated for some soils in the current study, it is likely that considerable reductions in the size of the error terms could be achieved with further sampling.

The total amount of C stored in the soils of the 22 1-km^2 squares of the study site was 1163×10^6 kg, although there was a wide range in the amount of C stored in the different soil types. As the range of C contents was highest when considering the total soil depth, the range in total C stored in each soil type was greatest when considering the total depth values. The soil type containing the most C was the Calluneto-Eriophoretum bog, a result of its large area and high C content. Though the Valley bog soil had, by far, the highest C content, it contained only a very small proportion of the study sites soil C since it covered only a very small area.

The soil C contained within individual kilometre squares in the study site varied greatly, being mainly a reflection of the proportion of Blanket bog soils in each square (Table 4). For example, square 20 contained a relatively small area of Blanket bog and had a total soil C storage of 22×10^6 kg. However, square 22 was almost completely covered by Blanket bog and was estimated to contain 75×10^6 kg of soil C.

The results clearly show that soils are far more important for C storage than vegetation in this ecosystem with soil containing at least 200 times more C than vegetation. The greater importance of soils for C storage has been shown in other studies; for example, Milne & Brown (1997) estimated soil C in Great Britain to be over 80 times greater than vegetation C, while Gorham (1991) estimated that vegetation accounted for only ≈ 1.5% of total terrestrial C in northern peatlands.

The importance of peat soils for C storage compared to mineral soils is clear at Moor House. Other studies have also shown peat soils to contain far greater amounts of C than other soils (see Post *et al*. 1982; Batjes 1996; Milne & Brown 1997). For example, Scottish peats have been estimated to contain between 46% (Milne & Brown 1997) and 75% (Howard *et al*. 1995) of the total soil C in Great Britain, while Eswaran *et al*. (1993) estimated C stored in histosols to be ≈ 22% of the global soil C pool, despite covering only 1.3% of the area.

Comparison with the UK national C inventory

The total C stored in vegetation for each 1-km^2 of the study site is shown in Table 5, together with the estimates of vegetation C for the same 1-km^2 squares from the UK national C inventory. On the whole, the values derived in this case study were higher than the national inventory estimates. In a few squares (e.g. squares 5 and 13) the estimates were very similar, although in others the national inventory estimate was less than one third of the value provided by this case study (e.g. squares 3 and 8). At 3.5×10^6 kg (Milne, pers. comm.), the overall estimate for vegetation C at Moor House by the national inventory was 35% lower than the case study value.

The squares where the difference between the case study and national inventory values was greatest tended to be on the eastern part of the study site where vegetation is dominated by heather moorland. In the case study, these vegetation classes were assigned a C content of 349 g C m^{-2} (e.g. Calluneto-Eriophoretum), although the equivalent values used in the national inventory were substantially lower (e.g. 200 g C m^{-2} for Heath and Bogs; Milne & Brown 1997).

Table 6 shows the values of soil C storage for each kilometre square determined in this case study and the national inventory for the 22 1-km^2 squares. The case study values used in this comparison were the values to a depth of 100 cm as these are comparable to the national

Table 5 Vegetation C storage in each kilometre square of the study site, showing values derived in this study and the national inventory estimate. National inventory values provided by R. Milne, Institute of Terrestrial Ecology.

Kilometre square no. (see Fig. 2)	Vegetation C (this study) ($kg \times 10^3$)	Vegetation C (national inventory) ($kg \times 10^3$)	Difference ($kg \times 10^3$)
1	223	122	101
2	310	137	173
3	340	98	242
4	343	227	116
5	106	115	–9
6	129	107	22
7	232	140	92
8	326	86	240
9	328	199	129
10	311	391	–81
11	335	256	79
12	129	156	–27
13	129	122	7
14	145	113	32
15	218	132	86
16	249	142	107
17	299	136	163
18	346	189	157
19	332	142	190
20	107	131	–24
21	109	135	–26
22	317	212	105
Total	5360	3488	1872

Table 6 Comparison of case study and national inventory estimates for soil C at Moor House, by kilometre square. All values are for the top 100 cm of soil. Units are $kgC \times 10^6$.

	Total C storage ($kg \times 10^6$)		
Kilometre square (see Fig. 2)	Soil C (this case study)	Soil C (national inventory)	Difference
1	34	113	80
2	36	113	77
3	39	113	74
4	38	113	75
5	27	113	86
6	26	113	87
7	35	113	78
8	39	113	74
9	36	113	77
10	38	113	75
11	41	113	73
12	23	113	90
13	25	113	88
14	25	113	88
15	33	113	80
16	36	113	77
17	37	113	76
18	36	113	77
19	41	113	72
20	20	113	93
21	23	34	11
22	42	113	71
Total	731	2412	1681

inventory values (the national inventory calculated soil C in England and Wales to a depth of 100 cm).

In all kilometre squares the case study values were lower than the national inventory values, with considerable differences between the two estimates for most squares; the national inventory value was about three times higher than the case study value in most squares and over five times higher in square 20. The square with the lowest difference between the two estimates was square 21, the only square which had been assigned, by the national inventory, a C storage value lower than the 113×10^6 kg estimated for the other squares.

When considering the 22 complete squares of the study site, the national inventory estimate was over three times higher than the case study value. There are several reasons that may account for these differences. The national inventory is based on soil maps of lower resolution than the one used in the case study. Furthermore, the resolution was even lower in the national inventory because only the dominant soil from each 1-km^2 square was used to derive C storage estimates (Milne & Brown 1997). For example, in the national inventory most 1-km^2 squares in the study site were classed as Winter Hill soil because the maps used by the national inventory indicated this was the dominant soil series in the squares. The C storage of each kilometre square classed as Winter Hill was derived using an estimate of C content for this soil type. Because 21 of the 22 squares at Moor House had been classified as Winter Hill, all but one of the squares had a C storage of 113×10^6 kg. Square 21 was classified as Wilcocks peaty gley because this soil was dominant, and had a lower C store of 34×10^6 kg. Since the national inventory simplified each kilometre square to only one soil type, variation within the square was overlooked, resulting in inaccuracies.

The kilometre square with the most similar C storage value in the two inventories was square 21. This suggests that the process of generalizing the squares to a single soil type, as in the national inventory, resulted in a misclassification of squares, or that the original soil maps used in the national inventory were inaccurate. Alternatively, the value of C content for the Winter Hill soil series may be too high and unrepresentative of the Moor House soils.

In the national inventory, the C content of the Winter Hill soil series, the main blanket bog soil type in England and Wales, has been estimated to be 113×10^6 kg km^{-2}, or 113 kg C m^{-2}. Because the national inventory estimates soil C in England and Wales only to a depth of 100 cm, the amount of C stored in the Winter Hill series must be to a depth of 100 cm. If it is assumed that the C content of peat is 50% as reported elsewhere (Heal & Smith 1978; Allen 1989; Immirzi *et al*. 1992), then the mean bulk density of the Winter Hill soil series must have been about 0.23 g cm^{-3}. This value is considerably higher than most published measurements of peat bulk density (≈ 0.1 g m^{-3}; Clymo 1983) and, therefore, it may be that the Winter Hill soil C content is atypical of blanket bog, and that an estimate derived from the sampling at Moor House would be more representative.

If we assume the Moor House values for C stored in the Winter Hill blanket bog are more representative for this soil type than the values used in the national inventory, we can make a new national soil C estimate to illustrate the inventory's sensitivity to unrepresentative soil C-values. The Winter Hill soil series covers an area of 2575 km^2 (based on the legend of the 1:250,000 Soil Map of England & Wales 1983) and, using the national inventory *C*-value for the Winter Hill soil series, contains 292×10^9 kg (i.e. $2575 \times 113 \times 10^6$ kg). However, the mean value of C stored in the 21 1-km^2 squares at Moor House classified as Winter Hill was 34×10^6 kg km^{-2}. If this value is used for the C content of the Winter Hill series, the total C contained in this soil in England and Wales becomes 88×10^9 kg (i.e. $2575 \times 34 \times 10^6$ kg). Thus, using the Moor House estimate of Winter Hill C content reduces the total soil C storage of England and Wales from 2890×10^9 kg to 2687×10^9 kg, a reduction of 7%. However, this new estimate assumes that the Moor House values for the C content in Winter Hill soils are more representative than the values in the national database; further sampling from other locations containing this important soil series are clearly necessary.

Implications for producing terrestrial C inventories

The Moor House results suggest that consideration of true surface areas is unlikely to greatly improve estimates of terrestrial C storage because true surface areas were only slightly larger than the 2D areas normally used for C inventories. However, Moor House is an area of upland moorland with relatively low vegetation C storage and if woodland had occupied the steeper slopes considerable underestimation of vegetation C stores may have occurred if only 2D areas had been used (e.g. Calluneto-Eriophoretum = 0.35 kg m^{-2}; broad-leaved woodland = ≈ 6 kg m^{-2}, Milne & Brown 1997). Consequently, it is suggested from the Moor House results that consideration of true surface areas will only significantly improve C storage estimates when vegetation of high C content (e.g. woodland) occupies steep slopes.

Inventories of vegetation C are likely to be more accurate than soil C inventories because vegetation is easier to map and sample. Consequently it is perhaps not surprising that the national inventory estimate for vegetation C appears more accurate than the soil C estimate. However, because far greater amounts of C exist within the soils at the site than vegetation, inaccuracy in the national inventory soil C estimate is of particular concern.

Many of the reported inventories of soil C have calculated C content to different depths, due for example, to the data being derived from soil surveys with different taxonomic requirements. For example, Batjes (1996) gives soil C densities for the soils of the world to the following depths: 0–30 cm, 0–50 cm, 0–100 cm and 0–200 cm. The UK's national C inventory uses soil C contents for the top 100 cm of soil for England and Wales, and the total soil depth for Scotland (Milne & Brown 1997). Other inventories have quantified soil C in the top 30 cm of soil only, because this is believed to be the most sensitive to climate change. In the present study, soil C has been calculated to a range of depths (30, 50, 100 cm and total depth) to enable the quantification of the underestimate made when determining C contents to depths less than the total soil depth. The results from Moor House show that soil C storage can be severely underestimated if quantified to depths below the total depth, with 432×10^6 kg or 37% of all soil C being stored below 100 cm depth.

Similarly, Eswaran *et al*. (1995) found that not estimating C storage to the complete soil depth could lead to a large underestimation in global soil C estimates. Although most soil types contained > 50% of C in the top 25 cm of the soil, Eswaran *et al*. (1995) found that organic soils had less than 7% of total C in the top 25 cm. At Moor House, underestimation of the soil C store due to not evaluating the entire profile was because of deep peat soils; although quantifying C storage to specific depths allows comparison between studies (Batjes & Sombroek 1997), soil C inventories may be considerable underestimates, particularly in areas with highly organic soils, if total soil depth is not considered.

The large difference in estimated soil C storage between this case study and the national inventory illustrates the difficulties in deriving inventories of soil C. Although Moor House contains soils of high C storage and high variability, the discrepancies in the estimates for this site mirror the uncertainty in both national and global estimates of soil C. For example, Howard *et al*. (1995) estimated the soil C content of Great Britain to be $21{,}784 \times 10^9$ kg, whilst a revised estimate produced by Milne & Brown (1997) of 9838×10^9 kg was over half the previous estimate. Estimates of global soil C have ranged from 700×10^{12} kg to 2946×10^{12} kg (see Post *et al*. 1982) and many recent estimates have fallen between these values (e.g. Eswaran *et al*. 1993; Batjes 1996). However, given that the UK's national inventory is one of the more detailed inventories of terrestrial C stores, and apparently overestimates the C storage at Moor House by a factor of three, the reliability of the existing global estimates of terrestrial C stores must be open to question.

Although the moorlands of the UK represent only a small fraction of the global terrestrial C store, the resource of information available for Moor House gave a unique opportunity to test the accuracy of an existing national C inventory. It is unlikely that similar datasets of such high quality are available within regions with much higher C storage such as the extensive Canadian and Russian peatlands, thus preventing similar assessments. However, the present study has clearly shown that detailed assessments of C inventories are required to gain a realistic understanding of their accuracy. As has been recognized by other authors (e.g. Gorham 1991; Eswaran *et al*. 1995), improving current inventories of global C storage requires further sampling and surveying of soil and vegetation at higher resolution.

Clymo (1996) considers that global-scale estimates of terrestrial C storage, such as Gorham's (1991) widely quoted value for northern peatlands, should be treated only as indicative, although there is no doubt of the importance of peatlands for C storage. However, accurate estimates of terrestrial C storage are required in order to provide quantitative estimates of potential terrestrial CO_2 sources. The so-called 'missing C sink' may at least partially be attributed to inaccurate estimates of C storage (Jain *et al*. 1997). The results presented in this paper suggest that there is considerable scope for improving inventories of terrestrial C stores, and that current estimates of global stores should be treated only as indications of the true size of the global terrestrial C store.

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Appendix

Correlation between Moor House and FAO soil classifications

Moor House soil type	Equivalent FAO class (FAO 1988)
Blanket bog	Dystric Histosols
Coarse scree	Coarse scree – Lithosols
Eroded blanket peat	Dystric Histosols
Peaty gley	Stagno-Dystric Gleysols
	Stagno-Dystric Gleysols
Peaty gley-peaty podzol	Placic-Podzols
Peaty podzol	Placic Podzols
Mixed bottom lands	Mixed soils – Dystric Cambisols
Red-brown limestone	Chromic Cambisols
Madeground	Disturbed ground
Peaty podzol-brown earth	Spodo-Dystric Cambisols
Solifluxion creep	Dystric and Eutric Cambisols complex
Fell top podzol	Orthic Podzols
Brown earth	Dystric Cambisols
Valley bog	Dystric Histosols